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TITLE: PET SCANNER WITH PHOTODECTORS AND WAVELENGTH SHIFTING FIBERS

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PET SCANNER WITH PHOTODETECTORS AND WAVELENGTH SHIFTING FIBERS

FIELD OF INVENTION

This invention relates to positron emission tomography ("PET") scanners, and in particular, to enhancing spatial and temporal resolution of a PET scanner.

BACKGROUND

In positron emission tomography ("PET"), a radioactive material is placed in the patient. In the process of radioactive decay, this material emits positrons. These positrons travel through the patient until they encounter electrons. When a positron and an electron meet, they annihilate each other. This results in emission of two gamma ray photons that exit the patient traveling in opposite directions. By detecting these pairs of gamma ray photons, one can infer where an annihilation event occurred, and thereby determine the distribution of the radioactive material within the patient.

To detect these pairs of gamma ray photons, (which will now be referred to as "gamma rays") it is useful to surround the patient with scintillating crystals. When a positron and electron annihilate within the patient, the resulting pair of gamma rays enter opposed scintillating crystals. These gamma rays then interact with the scintillation crystal. In so doing, they cause the emission of an isotropic spray of scintillation photons centered at a point at which the gamma ray interacts with the scintillation crystal. These scintillation photons can be detected by photodetectors in optical communication with the scintillation crystal.

Some of these scintillation photons are emitted in a direction that takes them to the photodetectors. Other scintillation photons, which are emitted in a direction away from any photodetector, nevertheless manage to reach a photodetector after being redirected by structures within the scintillating crystal. Yet other scintillation photons are absorbed and therefore never reach the photodetectors at all.

To detect gamma ray photons, the patient is positioned within a ring of scintillating crystals. Photodetectors observing the crystals can then detect the scintillation photons and provide, to a processor, information on how many scintillation photons were received and from which scintillation crystals they were received. The

processor then processes such data arriving from all photodetectors to form an image showing the spatial distribution of radioactive material within the patient.

Each photodetector provides a signal whose intensity indicates the number of scintillation photons reaching that photodetector. Because the photodetector has a large receiving cross section, it is able to detect many scintillation photons. As a result, the photodetector is able to determine, with great precision, when the gamma ray interacted with the material. However, the large receiving cross section of the photodetector limits its ability to provide precise information on where the gamma ray interacted with the scintillating crystal.

To enhance the spatial resolution of a PET scanner, one can place an array of wavelength-shifting, or fluorescent optical fibers in optical communication with the photomultipliers and the scintillation crystal. Scintillation photons can then enter the fluorescent optical fibers. In so doing, the scintillation photons are absorbed. This causes the optical fiber to fluoresce. The photons emitted within the fiber, which will be called "re-emitted photons", propagate toward a photosensor in optical communication with each fiber. Because the fluorescent optical fibers are much narrower than the photomultiplier tubes, the fiber array provides more spatial resolution than the photomultiplier tubes. This enables the fiber array to provide more precise information on where the gamma ray interacted with the scintillating crystal.

The small diameter of each fiber and the limited probability that the fiber will capture a scintillation photon, means that each fiber collects only a limited number of scintillation photons. As a result, the signal provided by the fiber array provides only limited temporal resolution. This makes it difficult to correlate signals from the fiber array with signals from the photomultipliers, particularly when the intervals between events are short.

SUMMARY

In one aspect of the invention, an apparatus includes photodetectors disposed to receive photons from a scintillator block of a PET scanner and configured to provide a

measured photodetector signal indicative of a distribution of photons detected by the photodetectors; and wavelength-shifting fibers disposed to receive photons from the scintillator block and configured to provide a measured fiber signal indicative of a distribution of photons received by the fibers.

Embodiments of this aspect of the invention may include one or more of the following features.

A processor is configured to estimate a location of a photon source based on the measured photodetector signal and on the measured fiber signal.

A processor is configured to estimate a location of a photon source based on a reference photodetector signal.

A processor is configured to estimate a location of a photon source based on a reference fiber signal.

A processor is configured to estimate an extent to which the estimated location is the correct location.

A stored calibration table contains values derived from the set of known photodetector signals.

A stored calibration table containing values derived from the set of known fiber signals.

The processor is configured to estimate a location of a photon source by estimating the likelihood that the measured photodetector signal and the measured fiber signal resulted from photons emitted at the photon source.

The processor is configured to estimate a location of a photon source by estimating the likelihood that the measured photodetector signal and the measured fiber signal resulted from photons emitted at each of a plurality of photon sources.

The processor is configured to estimate a location of a photon source by determining which of the photon sources is associated with the maximum likelihood that the measured photodetector signal and the measured fiber signal resulted from photons emitted at that photon source.

The processor is configured to estimate a location of a photon source by identifying, from a plurality of photon sources, a photon source having the property that the likelihood that the measured photodetector signal and the measured fiber signal resulted from photons emitted at that photon source is greater than the likelihood that the measured photodetector signal and the measured fiber signal resulted from photons emitted at a source other than that photon source.

The processor is configured to estimate a location of a photon source by estimating a first value indicative of a first likelihood, the first likelihood being the likelihood that the measured photodetector signal and the measured fiber signal resulted from photons emitted at a first photon source; estimating a second value indicative of a second likelihood, the second likelihood being the likelihood that the measured photodetector signal and the measured fiber signal resulted from photons emitted at a second photon source; determining, on the basis of the first and second values, that the first likelihood is greater than the second likelihood; and designating the first photon source to be the photon source from which from which the photons that caused the measured photodetector signal and the measured fiber signal were emitted.

Another aspect of the invention includes obtaining a measured photodetector signal indicative of a distribution of photons received by a plurality of photodetectors from a photon source on a scintillator block of a PET scanner; and obtaining a measured fiber signal indicative of a distribution of photons received by a plurality of wavelength-shifting fibers extending across the scintillator block from a photon source on a scintillator block.

Embodiments of this aspect of the invention may include one or more of the following features.

An additional step of estimating a location of the photon source on the scintillator block based on the measured photodetector signal and on the measured fiber signal.

Estimating a location of the photon source by estimating the location based on a reference photodetector signal.

Estimating a location of the most likely photon source by estimating the location based on a reference fiber signal.

Estimating an extent to which the estimated location is the correct location.

The additional step of reading a stored calibration table containing values derived from the set of known photodetector signals.

The additional step of reading a stored calibration table containing values derived from the set of known fiber signals.

Estimating a location of the photon source by estimating the likelihood that the measured photodetector signal and the measured fiber signal resulted from photons emitted at the photon source.

Estimating a location of a photon source by estimating the likelihood that the measured photodetector signal and the measured fiber signal resulted from photons emitted at each of a plurality of photon sources.

Estimating a location of a photon source by determining which of the photon sources is associated with the maximum likelihood that the measured photodetector signal and the measured fiber signal resulted from photons emitted at that photon source.

Estimating a location of a photon source by identifying, from a plurality of photon sources, a photon source having the property that the likelihood that the measured photodetector signal and the measured fiber signal resulted from photons emitted at that photon source is greater than the likelihood that the measured photodetector signal and the measured fiber signal resulted from photons emitted at a source other than that photon source.

Estimating a location of a photon source by estimating a first value indicative of a first likelihood, the first likelihood being the likelihood that the measured photodetector signal and the measured fiber signal resulted from photons emitted at a first photon source; estimating a second value indicative of a second likelihood, the second likelihood being the likelihood that the measured photodetector signal and the measured fiber signal resulted from photons emitted at a second photon source; determining, on the basis of the first and second values, that the first likelihood is greater than the second likelihood; and designating the first photon source to be the photon source from which from which the photons that caused the measured photodetector signal and the measured fiber signal were emitted.

Another aspect of the invention includes a computer-readable medium on which is encoded software for estimating a location of a most-likely photon source on a scintillator block. The software includes instructions for obtaining a measured photodetector signal indicative of a distribution of photons received by a plurality of photodetectors from a photon source on a scintillator block, obtaining a measured fiber signal indicative of a distribution of photons received by a plurality of wavelength-shifting fibers extending across the scintillator block from a photon source on a scintillator block; estimating a location of a most-likely photon source on the scintillator block at least in part on the basis of the measured photodetector signal and at least in part on the basis of the measured fiber signal.

Embodiments of this aspect of the invention may include one or more of the following features.

The instructions for estimating a location of a most-likely photon source include instructions for comparing the measured photodetector signal with a set of known photodetector signals and comparing the measured fiber signal with a set of known fiber signals.

The software further includes instructions for reading a stored calibration table containing values derived from the set of known photodetector signals.

The software further includes instructions for reading a stored calibration table containing values derived from the set of known fiber signals.

The instructions for estimating a location of a most-likely photon source include instructions for estimating the likelihood that the measured photodetector signal and the measured fiber signal resulted from photons emitted at the most-likely photon source.

The instructions for estimating a location of a most-likely photon source include instructions for estimating the likelihood that the measured photodetector signal and the measured fiber signal resulted from photons emitted at each of a plurality of photon sources; and determining which of the plurality of photons sources is associated with the maximum likelihood that the measured photodetector signal and the measured fiber signal resulted from photons emitted at that photon source.

The instructions for estimating a location of a most-likely photon source include instructions for estimating the likelihood that the measured photodetector signal and the measured fiber signal resulted from photons emitted at a each of a plurality of photon sources; and identifying, from the plurality of photon sources, a most-likely photon source having the property that the likelihood that the measured photodetector signal and the measured fiber signal resulted from photons emitted at the most-likely photon source is greater than the likelihood that the measured photodetector signal and the measured fiber signal resulted from photons emitted at a source other than the most-likely photon source.

The instructions for estimating a location of a most-likely photon source include instructions for estimating a first value indicative of a first likelihood, the first likelihood being the likelihood that the measured photodetector signal and the measured fiber signal resulted from photons emitted at a first photon source; estimating a second value indicative of a second likelihood, the second likelihood being the likelihood that the measured photodetector signal and the measured fiber signal resulted from photons emitted at a second photon source; determining, on the basis of the first and second values, that the first likelihood is greater than the second likelihood; and designating the first photon source to be the most-likely photon source.

Unless otherwise defined, all technical and scientific terms used herein have the same meaning as commonly understood by one of ordinary skill in the art to which this invention belongs. Although methods and materials similar or equivalent to those described herein can be used in the practice or testing of the present invention, suitable methods and materials are described below. In case of conflict, the present specification, including definitions, will control. In addition, the materials, methods, and examples are illustrative only and not intended to be limiting.

Other features and advantages of the invention will be apparent from the following detailed description, and from the claims.

BRIEF DESCRIPTION OF THE FIGURES

FIG. 1 shows a ring of modules;

FIGS. 2A and 2B show a detector block;

FIG. 3 shows the detector block of FIGS. 2A and 2B taken along the line 3-3;

FIG. 4 shows master/slave relationships between a subset of the modules shown in FIG. 1;

FIG. 5 shows connections between a master and its two slaves;

FIG. 6 is a flow-chart of a process carried out by a slave;

FIG. 7 is a flow-chart of a process carried out by a master;

FIG. 8 shows a characteristic temporal distribution of scintillation photons arising from an interaction in a scintillation crystal.

FIG. 9A-C show exemplary response curves for detector blocks;

FIG. 10 is a cross-section of a structured optical element;

FIG. 11 is a plan view of the inner layer of the structured optical element of FIG. 10 taken along the line 11-11; and

FIG. 12 is a plan view of the structured outer layer of the structured optical element of FIG. 10 taken along the line 12-12.

DESCRIPTION

Referring to FIG. 1, a PET scanner **10** includes a ring **12** of detector modules **16A-K** surrounding a bed **14** on which a patient **15** is to lie. Each detector module **16A-K** (referred to as a "module") includes one or more rows of detector blocks **17**. A detector block **17**, shown in FIG. 2A, includes, for example, four photomultiplier tubes **19A-D** arranged in a 2x2 array in optical communication with a scintillator block **21**. The scintillator block **21** is typically made of CsI(Na) (sodium doped cesium iodide). Photomultiplier tubes **19A-B** are visible in FIG. 2A and photomultiplier tubes **19A-C** are visible in FIG. 2B. The remaining photomultiplier tube **19D**, which lies diagonally across the array from photomultiplier tube **19A** is not visible.

The scintillator block **21** is divided into individual pillars **23** made of a scintillating crystal. The pillars **23** are arranged in an array, for example a 10x16 array, a portion of which is shown in FIG. 3. The array has a rectangular cross-section with a length of 3.22 inches (82 millimeters) and a width of 2.69 inches (68 millimeters).

Each pillar **23** in the array is a rectangular prism having a transverse cross-section with a long side **25** and a short side **27**. The axis parallel to the long side **25** will be referred to herein as the "major" axis of the scintillator block **21**, and the axis parallel to the short side **27** of the will be referred to herein as the "minor" axis of the scintillator block **21**.

To image a portion of a patient with a PET scanner **10**, one introduces a radioactive material into the patient. As the radioactive material decays, it emits positrons. A positron, after traveling a short distance through the patient, eventually encounters an electron. The resulting annihilation of the positron and the electron generates two gamma ray photons traveling in opposite directions. To the extent that neither of these gamma ray photons is deflected or absorbed within the patient, they emerge from the patient and strike two opposed pillars **23**, thereby generating two flashes of light (referred to as "events") indicative of an annihilation occurring within the patient.

By determining from which pillars **23** these light flashes originated, one can estimate where in the patient the annihilation event occurred.

In particular, referring again to FIG. 1, when one of these gamma ray photons strikes a pillar in a first detector module **16A**, the other gamma ray photon strikes a pillar in a second detector module **16E, F, G,** or **H** opposite the first detector module. This results in two events: one at the first detector module **16A** and the other at the opposed second detector module **16E, F, G,** or **H**. Each of these events indicates the detection of a gamma ray photon. If these two events are detected at the first detector module **16A** and the second detector module **16E, F, G,** or **H** at almost the same time, it is likely that they indicate an annihilation occurring on a line connecting first detector module **16A** and the second detector module **16E, F, G,** or **H.**

It is apparent that what is of interest in PET scanning are pairs of events detected by opposed detector modules **16A**, **16E-F** at, or almost at, the same time. A pair of events having these properties is referred to as a "coincidence." In the course of a PET scan, each detector module **16A-K** detects a large number of events. However, only a limited number of these events represent coincidences.

Associated with each detector module **16A-K** is a module processor **18A-K** that responds to events detected by its associated detector module **16A-K**. A module processor **18A-K** includes a processing element and a memory element in data communication with each other. The processing element includes a computational element containing combinatorial logic elements for performing various logical operations, an instruction register, associated data registers, and a clock. During each clock interval, the processor fetches an instruction from the memory element and loads it into the instruction register. Data upon which the instruction is to operate is likewise loaded into the associated data registers. At subsequent clock intervals, the processing element executes that instruction. A sequence of such instructions is referred to herein as a "process."

Each module processor **18A-K** executes a master process and a slave process concurrently. Each module processor **18A-K** is simultaneously a master of two module

processors and a slave to two other module processors. As used herein, “master” shall mean a module processor **18A-K** acting as a master module processor and “slave” shall mean a module processor **18A-K** acting as a slave module processor. The terms “master module” and “slave module” shall be used to refer to the detector modules **16A-K** associated with the master and slave respectively.

The two slaves of each master are selected on the basis of the relative locations of their associated detector modules **16A-K** on the ring **12**. In particular, the slaves of each master are selected to maximize the likelihood that an event detected at the master detector module and an event detected at any one of the slave detector modules form a coincidence pair.

For the configuration of eleven detector modules shown in FIG. 1, the master/slave relationships among module processors **18A-K** are as follows:

MASTER	SLAVE_1	SLAVE_2
18A	18E	18F
18B	18F	18G
18C	18G	18H
18D	18H	18I
18E	18I	18J
18F	18J	18K
18G	18K	18A
18H	18A	18B
18I	18B	18C
18J	18C	18D
18K	18D	18E

and thus the slave/master relationships among module processors **18A-K** are as follows:

SLAVE	MASTER_1	MASTER_2
18A	18G	18H

18B	18H	18I
18C	18I	18J
18D	18J	18K
18E	18K	18A
18F	18A	18B
18G	18B	18C
18H	18C	18D
18I	18D	18E
18J	18E	18F
18K	18F	18G

FIG. 4 shows the ring **12** of FIG. 1 with lines added to show the master/slave relationships of two of the eleven module processors. The lines connecting detector modules **16A** to **16E** and detector modules **16A** to **16F** indicate that module processors **18E** and **18F** are slaves of module processor **18A**. Module processor **18F** has its own two slaves, as indicated by the lines connecting detector module **16F** to detector modules **16J** and **16K**. The eighteen lines representing the remaining master/slave relationships are omitted for clarity.

As shown in FIG. 5, a master **18A** is connected to its first slave **18E** by first and second data links **20A, 22A**. Similarly, the master **18A** is connected to its second slave **18F** by additional first and second data links **20B, 22B.** The first and second data links **20A-B, 22A-B** are used to transmit trigger pulses between the master **18A** and the corresponding slave **18E-F**. Hence, the first and second data links **20A-B, 22A-B** are typically each a single wire.

When a slave **18E** receives, from its associated detector module **16E,** a signal indicative of an event (hereinafter referred to as a "slave event"), it transmits a pulse to the master **18A** on the first data link **20A**. When the master **18A** considers a slave event detected by the slave **18E** to be a constituent event of a coincidence, it sends a pulse back to that slave **18E** on the second data link **22A**.

A third data link **24A-B**, which is typically an LVDS ("low-voltage differential standard") channel connects the master **18A** and each of its slaves **18E-F**. The slaves **18E-F** use this third data link **24A-B** to transmit to the master **18A** additional information about slave events. Such additional information can include, for example, the energy of the incident gamma ray photon that triggered that slave event and the waveform of the voltage signal generated by the photo multiplier tube.

FIG. 6 shows the procedure carried out by a slave. Upon receiving, from its associated module processor, a signal indicative of a slave event (step **26**), a slave reports the detection of that slave event to both of its respective masters (steps **28A-B**). It does so by transmitting a pulse on each of two first data links that connect it to those masters. The slave then waits for a response from its masters on either of the two second data links connecting it to each of those two masters (steps **30A-B**).

In response to a request pulse received on the second data link from a master, the slave prepares a data packet containing additional information about the slave event (steps **32A-B**). This data packet is then transmitted on the third data link to whichever of its masters requested that additional information (steps **34A-B**). After sending the data packet, the slave waits for the next event (step **36**). If neither master sends a request pulse within a pre-defined time interval, the slave discards the slave event (step **38**) and waits for the next slave event (step **36**).

FIG. 7 shows the procedure carried out by a master. Upon receiving, from its associated detector module, a signal indicative of a slave event (step **40**), the master compares the occurrence time of that slave event with occurrence times of events (hereinafter referred to as "master events") received by its own associated detector module (step **42**). If the occurrence times of a master event and a slave event differ by no more than a selected tolerance, the master considers that master event and that slave event to be a coincidence (step **44**). Otherwise, the master ignores the slave event and waits for the next slave event (step **46**).

Upon recognizing a coincidence between a master event and a slave event, the master transmits a request pulse to whichever slave detected that slave event (step **48**). As

described in connection with FIG. 6, this pulse is interpreted by the slave as a request for additional information about that slave event. The master then waits for the data packet containing additional information about the slave event.

Upon receiving the data packet (step **50**), the master creates a coincidence record that includes information about the master event and the slave event that together make up the coincidence. This coincidence record is stored on a mass storage medium, such as a magnetic disk or a magnetic tape, (step **52**) for later processing by an image-reconstruction process executing known tomography algorithms.

As described, each slave has two masters and each master has two slaves. However, there is no requirement that a slave have a particular number of masters or that a master have a particular number of slaves. Nor is there a requirement that each master have the same number of slaves or that each slave have the same number of masters.

The illustrated PET scanner **10** has eleven detector modules. However, a different number of detector modules can be used. The invention does not depend on the number of detector modules in the ring **12**. It is topologically convenient, however, to have an odd number of detector modules.

In FIG. 6, the slave notifies the master of an event but withholds the information about the event until the master actually requests that information. This minimizes the probability that the third data link will be busy ferrying data packets from the slave to the master, thereby minimizing the probability that a data packet will be dropped. However, it also imposes some additional complexity since the master must now request data packets of interest.

Alternatively, the slave sends the master a data packet for each event detected at that slave's associated detector module. If the master does not consider the event to be part of a coincidence, it simply discards the data packet. This eliminates the need for the second data link since the master no longer has to signal the slave to send a data packet.

Referring back to FIGS. 2-3, each detector block **17** also includes wavelength-shifting optical fibers **54** extending parallel to the major axis of each row of pillars on the

face of the scintillator block **21** nearest the object being imaged. The fibers **54** are spread across the face of the scintillator block **21**, in a fiber array **53** as shown in FIG. 3, with one fiber **54** extending parallel to the major axis of each row of pillars **23**. Each fiber **54** is in optical communication with a fluoremeter **55** that provides a signal to a respective processor **18A-K**.

The walls of the fibers **54** are transparent to light emerging from the pillars **23**. As a result, light that originates in one of the pillars **23** (the shaded pillar in FIG. 3) adjacent to a fiber **54** will introduce light into that fiber **54**. A portion of this light is trapped within the fiber **54** and guided to the fluoremeter **55** associated with that fiber **54**. By observing the spatial distribution of light across the detectors, and hence across the fibers **54**, the processor **18A-K** can determine from which row of pillars **23** of the scintillator block **21** the light originated. A PET scanner incorporating a ribbon of fibers **54** in this manner is described in U.S. Patent No. 5,600,144, the contents of which are incorporated by reference.

The spray of scintillation photons during an event has a characteristic temporal distribution, shown in FIG. 8. As shown in FIG. 8, a sharp rise in the number of scintillation photons marks the moment of interaction between a gamma ray photon and the scintillation block **21**. This is followed by a gradual decrease in the number of scintillation photons. The ability to determine precisely the moment of interaction depends in part on the ability to detect the sharp rise shown in FIG. 8.

If a detector could somehow detect all the scintillation photons emitted by the interaction, a measured temporal distribution of scintillation photons would match the actual temporal distribution shown in FIG. 8. However, at any instant, a detector can detect only those photons that travel toward that detector. The number of such photons is subject to statistical fluctuations. When the number of such photons is small, the measured temporal distribution of scintillation photons may be very different from the characteristic temporal distribution shown in FIG. 8. This adversely affects the ability to identify the precise moment of interaction.

The photomultiplier tube **19A-D**, because of its large receiving cross-section, samples a large number of photons from the characteristic temporal distribution shown in FIG. 8. Because of this, the statistical fluctuations become less significant, and the temporal distribution as measured by a photomultiplier tube **19A-D** tends to match the characteristic temporal distribution shown in FIG. 8. A photomultiplier tube **19A-D** is thus able to determine the moment of impact with great precision, thereby enabling it to resolve events that occur very closely together in time. However, because of its large receiving cross-section, the photomultiplier tube **19A-D** has poor spatial resolution, and is therefore unable to resolve events that occur very closely together in space.

In contrast, a fiber **54**, because of its smaller receiving cross-section, provides finer spatial resolution than a photomultiplier tube **19A-D**. However, the limited light-trapping efficiency of a fiber **54** prevents it from sampling as many scintillation photons as a photomultiplier tube **19A-D**. Because of this, the temporal distribution as seen by the fiber **54** often looks quite different from the actual temporal distribution in FIG. 8. In particular, the sharp rise associated with the moment of interaction is often degraded. As a result, although the fiber array **53** can discriminate between events that occur very close to each other in the scintillation block **21**, it cannot easily resolve events that occur very closely together in time.

The spatial resolution of the photomultiplier tubes **19A-D** depends, in part, on the number of photomultiplier tubes **19A-D**. For example, one could provide a large number of photomultiplier tubes, each with a smaller receiving cross-section. However, this would result in fewer scintillation photons being collected by each photomultiplier tube, thereby degrading the sharp rise associated with the moment of interaction as discussed above in connection with the fibers **54.** Moreover, because of the expense of photomultiplier tubes, it is desirable to reduce the number of photomultiplier tubes while maintaining adequate spatial resolution. This is achieved by a providing a light mixer **56** positioned between the photomultiplier tubes **19A-D** from the scintillator block **21**.

The light mixer **56** is a layer of optically transparent material. An interface **59** between the scintillator block **21** and the light mixer **56** is coated with an index-matching

layer to reduce reflections at that interface **59**. Similarly, an interface **57** between the light mixer **56** and the photomultiplier tubes **19A-D** is coated with an index-matching layer to reduce reflections at that interface **57**.

A gamma ray photon entering a pillar **23** generates an isotropic spray of scintillation photons. These scintillation photons are scattered or reflected by structures within the optical element. Depending on which pillar the scintillation photons originate from, different numbers of scintillation photons strike the photomultiplier tubes **19A-D**. As a result, the first, second, third and fourth photomultiplier tubes **19A-D** generate corresponding first, second, third and fourth photomultiplier signals that depend on the number of scintillation photons detected by that photomultiplier tube **19A-D**.

Ideally, the ratio of the sum of the first and third photomultiplier signals and the sum of all four photomultiplier signals depends linearly on the value of the second coordinate associated with the pillar **23** that emitted the light. Similarly, the ratio of the sum of the first and second photomultiplier signals and the sum of all four photomultiplier signals depends linearly on the value of the first coordinate associated with the pillar **23** that emitted the light. Exemplary ideal ratios are shown by the solid lines **58, 60** in FIGS. 9A and 9B. In addition, the sum of all four photomultiplier signals should be the same, no matter which pillar **23** emits the light, as shown by the solid line **62** in FIG. 9C.

To avoid both non-linearity and crowning, a preferred optical element **70**, shown in FIG. 10, is a structured optical element having a mixing layer **72** adjacent to the scintillator block **21**, an unstructured cap layer **74** adjacent to the photomultiplier tubes **19A-D**, a structured outer layer **76** adjacent to the cap layer **74**, and a structured inner layer **78** between the mixing layer **72** and the structured outer layer **76**. The four layers are all made of an optically transparent medium.

The mixing layer **72** of the optical element **70** is a layer of transparent material between approximately 0.05 and 0.12 inches thick, and preferably 0.08 inches thick. This mixing layer **72** permits light to mix freely for a short distance before entering the structured inner layer **78**.

Referring to FIG. 11, the structured inner layer **78** includes an optically transparent central region **80** having an outer wall **82** extending parallel to the sides of the optical element **70** and an optically transparent peripheral region **84** having an inner wall **86** extending parallel to, but offset from, the outer wall **82** of the central region **80**. As used here, "inner wall **86**" refers to a surface that is in physical contact with the peripheral region **84** and "outer wall **82**" refers to a surface that is in physical contact with the central region **80**. The inner and outer walls **86, 82** thus define a rectangular gap **88** that separates the central region **80** from the peripheral region **84**. The rectangular gap **88** can be filled with air or a material having a dielectric constant different from that of the optically transparent medium, thereby promoting total internal reflection within the central region **80** and the peripheral region **84**. The width of the gap **88** is not critical, however it should be greater than a wavelength to suppress coupling across the gap **88.**

The rectangular gap **88** can be offset from the walls of the mixer **70** so that exactly one pillar **23** lies underneath the peripheral region **84**. This is advantageous because all photons emerging from the same pillar will then be subjected to the same physical environment. However, this is not required. The rectangular gap **88** can, for example, bisect a pillar **23**.

The inner wall **86** of the peripheral region **84** is highly polished, so that scintillation photons in the peripheral region **84** that are incident on the inner wall **86** are specularly reflected. In contrast, the outer wall **82** of the central region **80** is roughened, so that scintillation photons in the central region **80** that are incident on the outer wall **82** are reflected in a random direction. As a result, the probability that a scintillation photon in the peripheral region **84** will reach the photomultiplier tube is greater than the probability that a scintillation photon in the central region **80** will reach the photomultiplier tube. This tends to enhance the response of the photomultiplier tubes **19** to scintillation photons in the peripheral region **84** relative to the response of the photomultiplier tubes **19** to scintillation photons in the central region **80**.

The dashed line **68** in FIG. 9C can be interpreted as a probability density function indicative of the likelihood that a scintillation photon originating at a particular value of

the second coordinate will reach a photomultiplier tube **19A-D**. In the conventional optical element, the probability density function **68** is non-uniform because scintillation photons originating in the central region **80** are more likely to reach the photomultiplier tube **19A-D** than are scintillation photons originating in the peripheral region **84**. The structured inner layer **78**, by encouraging photons from the peripheral region **84** to reach the photomultiplier tubes **19A-D** and simultaneously discouraging scintillation photons from the central region **80** from reaching the photomultiplier tubes **19A-D**, tends to flatten the probability density function **68**. This tends to make the sum of the first and second photomultiplier signals independent of the second coordinate.

Referring now to FIG. 12, the structured outer layer **76** of the optical element **70** is made up of four optically transparent quadrants **90A-D**, one corresponding to each photomultiplier tube **19A-D**. Each quadrant **90A** has two outer walls **92A**, **92B** that meet at an exterior corner **94A** and two inner walls **96A, 96B** that meet at an interior corner **98A**. As used here, the inner walls **96A, 96B** are in physical contact with the quadrant **90A** with which they are associated. The inner walls **96A, 96B** of each quadrant **90A** are highly polished so that scintillation photons incident thereon are specularly reflected.

Collectively, the inner walls **96A, 96B** of all four quadrants **90A-D** form a cruciform gap **100** extending across the structured outer layer **76** in the directions of both the major axis and the minor axis. The cruciform gap **100** can be filled with air or a material having a dielectric constant different from that of the optically transmitting medium, thereby promoting total internal reflection within each quadrant **90A-D**. The width of the gap **100** is not critical, however it should be greater than a wavelength to suppress coupling across the gap **100.**

The structured inner layer **78** is 0.923 inches (16.8 mm) thick and the total thickness of the optical element **70** is 1.573 inches (39.9 mm). An optically transmissive layer **102,** like the mixing layer **72,** is optionally placed between the structured outer layer **76** and the structured inner layer **78**. This optional layer **102** is approximately .15 inches (3.8 mm) thick. The length and width of the optical element **70** are 3.21 inches (81.8 mm) and 2.695 inches (94.4 mm) respectively. The cap layer **74** of optically transparent

material can be placed over the structured outer layer **76**, thereby preventing foreign matter from falling into the cruciform gap **100**. This cap layer **74** is between 0.06 inches and 0.12 inches.

In the embodiment described here, there are four photomultiplier tubes **19A-D** arranged in a grid. Hence, there are four regions **90A-D** within the structured outer layer **76**. The regions are disposed on the structured outer layer **76** so that each region **90A** faces one **19A** of the four photomultiplier tubes **19A-D**. The resulting gap between the regions is thus a cruciform gap **100**.

In other embodiments, there may be more than four photomultiplier tubes arranged in a rectangular array. In such cases, there will be a corresponding number of regions within the structured outer layer **76**, with each region facing a corresponding photomultiplier tube. The resulting gap between regions will then define a grid. The walls defining the gap are highly polished so that scintillation photons incident on a wall from a particular region are specularly reflected back into that region.

In embodiments having many photomultiplier tubes, a structured inner layer **78** can have several nested peripheral regions surrounding the central region. These additional regions are shaped like the peripheral region and are separated from each other by gaps. Each gap has an inward-facing wall and an outward-facing wall. The inward-facing wall is roughened to discourage specular reflection and the outward-facing wall is highly polished to encourage specular reflection. The degree of roughening and polishing of each pair of inward-facing and outward-facing walls can change from one pair to the next, thereby enabling one to tune the inner layer to achieve the flattest possible response.

The optical element **70** is formed by casting the individual layers. The layers are then glued together with an index matching adhesive between the layers. To facilitate removal of the structured outer layer **76** and the structured inner layer **78** from the mold, the rectangular gap **88** and the cruciform gap **100** are typically made with a V-shaped profile.

In identifying at what time and at what pillar **23** an interaction takes place, it is advantageous to use both the information provided by the photomultiplier tubes **19A-D** and that provided by the fiber array **53**. With its superior temporal resolution, the photomultiplier tubes **19A-D** would contribute information identifying when an event took place. With its superior spatial resolution, the fiber array **53** would contribute information identifying where the event took place.

A difficulty in simultaneously exploiting information provided by the photomultiplier tubes **19A-D** and by the fiber array **53** arises from the difficulty in correlating events detected by the photomultiplier tube **19A-D** with events detected by the fiber array **53** when using a CsI(Na) scintillator block **21**. A fiber **54** can resolve events separated by approximately 100 nanoseconds, whereas a photomultiplier tube **19A-D** can resolve events separated by as little as 1 nanosecond. If the photomultiplier tubes **19A-D** were to detect two events occurring less than 100 nanoseconds apart, it would be difficult to reliably identify the corresponding events as detected by the fiber array **53**.

One method of associating events detected by the photomultiplier tubes **19A-D** with those detected by the fiber array **53** is to first calibrate the detector modules **16A-K**. During calibration, a 511 kEV gamma ray photon is made to enter a known pillar **23**, thereby causing a spray of photons originating from that pillar **23**. A subset of these photons reaches the photomultiplier tubes **19A-D** and triggers a photomultiplier signal. A smaller subset of these photons reaches the fiber array **53** and triggers a fiber signal. The photomultiplier signal and the fiber signal are both recorded and identified as being associated with an interaction occurring in the known pillar **23**.

The foregoing procedure is repeated many times. With each repetition, a new photomultiplier signal and a new fiber signal are generated and recorded. The resulting set of recorded fiber signals is then averaged together to obtain a baseline fiber response to an interaction occurring within the known pillar **23**. Similarly, the resulting set of recorded photomultiplier signals is averaged together to obtain a baseline photomultiplier response to an interaction occurring within the known pillar **23**.

The calibration procedure for a known pillar **23**, as set forth above, is repeated for each pillar **23** in the detector module **16A-K**. The end result of the calibrating procedure is thus a pair of calibration tables: a photomultiplier calibration table and a fiber calibration table. The photomultiplier calibration table shows, for each pillar **23**, the baseline photomultiplier response to an interaction occurring in that pillar **23**. The fiber calibration table shows, for each pillar **23**, the baseline fiber response to an interaction occurring in that pillar **23**.

When the PET scanner **10** is in use, the photomultiplier tubes **19A-D** will periodically generate measured photomultiplier signals in response to interactions occurring at unknown pillars at uncertain times. A measured photomultiplier signal will in general be different from any of the baseline photomultiplier responses available in the photomultiplier calibration table. Nevertheless, a measured photomultiplier signal represents a sample from a sample space of photomultiplier signals having a known average: namely the baseline photomultiplier response. As a result, it is possible to calculate, using known discrete maximum likelihood methods, the likelihood that the measured photomultiplier signal comes from a sample space having, as its average, the known baseline photomultiplier response.

Similarly, when the PET scanner **10** is in use, the fiber array **53** will periodically generate received fiber signals in response to interactions occurring at unknown pillars at uncertain times. A measured fiber signal will in general be different from any of the baseline fiber responses available in the fiber calibration table. Nevertheless, a measured fiber signal represents a sample from a sample space of fiber signals having a known average: namely the baseline fiber response. As a result, it is possible to calculate, using known discrete maximum likelihood methods, the likelihood that the measured fiber signal comes from a sample space having, as its average, the known baseline fiber response.

To determine whether a measured fiber signal and a measured photomultiplier signal are associated with each other, a module processor calculates, for each pillar **23**, the likelihood that the measured fiber signal and the measured photomultiplier signal

were generated by an interaction occurring in that pillar **23**. The pillar **23** for which this likelihood is the highest is referred herein as the "most likely pillar." If the likelihood associated with the most likely pillar is in excess of a selected threshold, then the measured fiber signal and the measured photomultiplier signal are considered to have been generated by the same interaction at that pillar **23**.

It is also possible to calculate, using known statistical techniques, the probability that the most likely pillar is indeed the correct pillar. Such techniques include calculating likelihood ratios in which the numerator is the probability that the most likely pillar is the correct pillar and the denominator is a sum of the foregoing probability and the probability that another pillar, for example the next most-likely pillar, is the correct pillar. Such a ratio would provide a measure of the quality of the estimate.

The foregoing method can also be adapted to cases in which the actual probabilities are not known. In such cases, a quantity whose value is correlated with the actual probability can be used instead.

Other implementations are within the scope of the following claims.